Commissioning of the Fermilab Accelerators for NuMI Operation

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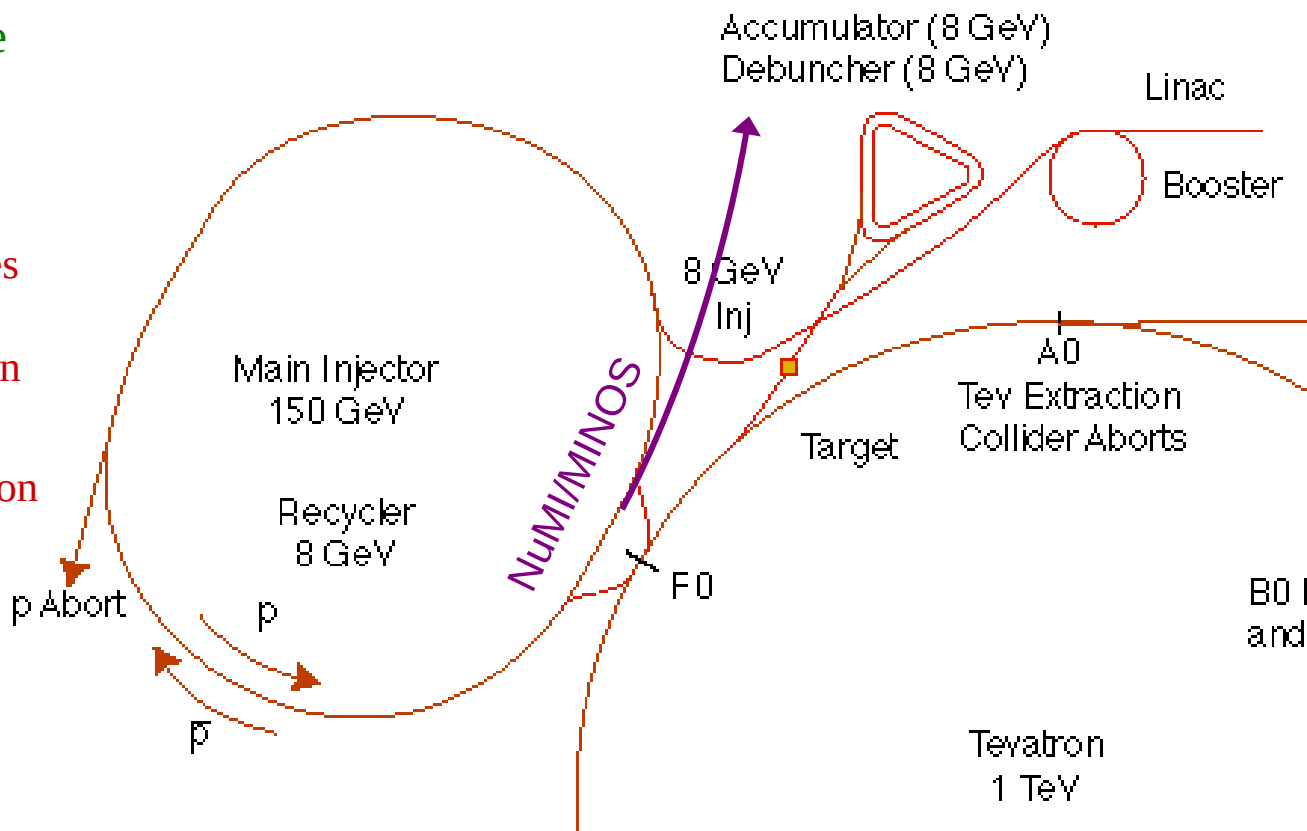
Fermilab as a Proton Source

- Protons accelerated to 8 GeV in Booster
  - 474 m Circumference
  - 5 x 10^{12} protons / batch (maybe 6 x10^{12})
  - 15 Hz repetition rate

- Main Injector accelerates to 120 GeV
  - 3320 m Circumference (7x Booster)
  - Multiple batches of Booster beam injected
    - As many as 6 batches
    - 1 must go for antiproton production
  - Cycle time > 1.9 s
    - Depends on antiproton source needs



Protons for NuMI

- Proton Math: $\frac{\text{protons}}{\text{year}} = \frac{\text{protons}}{\text{Booster Batch}} \times 5 \frac{\text{Booster Batches}}{\text{MI Cycle}} \div \tau \frac{\text{seconds}}{\text{MI Cycle}} \times 1.9\text{E}7 \frac{\text{seconds}}{\text{year}}$
- MINOS initial request: 8 x 10^{20} protons
  - 4 x 10^{13} / pulse $\Rightarrow$ 2.5 x 10^{13} / pulse
  - 4 x 10^{20} / year $\Rightarrow$ 2.5 x 10^{20} / year
  - Request has not decreased
- MINOS 5 year plan
    - http://hep.caltech.edu/~michael/numipiwg/fiveyear/fiveyear.ps
  - Calls for increasing proton rate $\rightarrow$ 7.5 x 10^{20} / year
  - Various small improvements
    - c.f. Finley Report: http://www.fnal.gov/directorate/program_planning/studies/ProtonReport.pdf
- Prospects of a proton driver
  - Potentially increase to 20 x 10^{20} / year
    - http://www.fnal.gov/directorate/Longrange/ProtonDriver_Open_Meeting.html

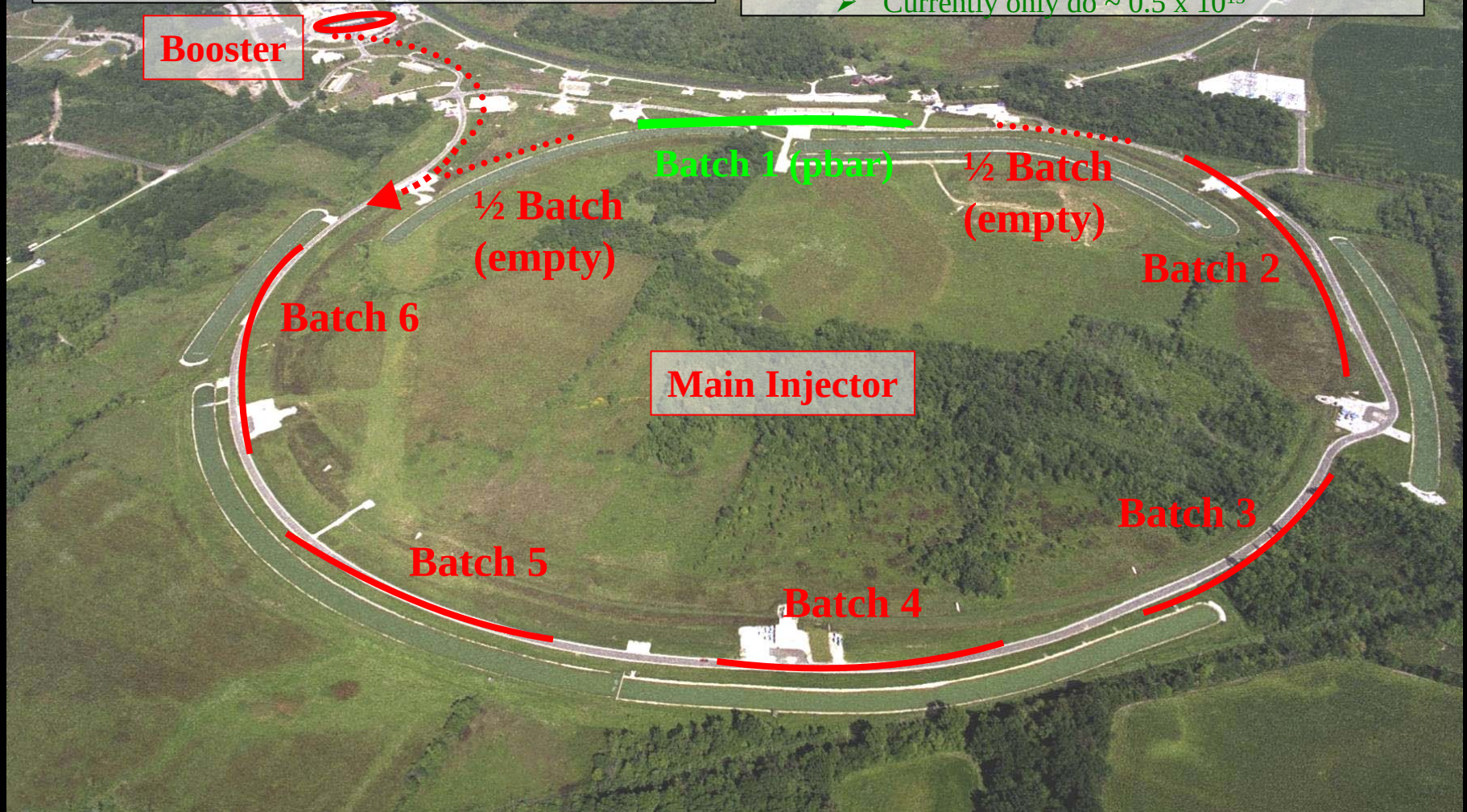
Challenges to NuMI

- Must coexist with collider program
  - Involves accelerating two beams in MI, simultaneously
  - Timing issues are shared
    - PBar cooling time
- Requires high performance of accelerators
  - Well in excess of previous levels of operation
- Beam quality requirements
  - Cannot afford high losses in NuMI primary line
- Main Injector issues
  - Multibatch commissioning
  - 8 GeV lifetime
  - Dampers
  - Beam Permit
  - RF Power
- Booster Issues
  - Intensity
  - Losses & radiation
  - Multibatch timing

Main Injector Commissioning

- Main Injector has not operated in multibatch mode
  - Not necessary yet
- NuMI will require continuous multibatch operation
  - Simultaneous with antiproton production

- Two beams must be accelerated together
  - Extracted to PBar & NuMI
- Total intensity is more than six time the current running
  - 2.5 x 10^{13} for NuMI
  - .8-1.0 x 10^{13} for PBar
  - Currently only do ~ 0.5 x 10^{13}

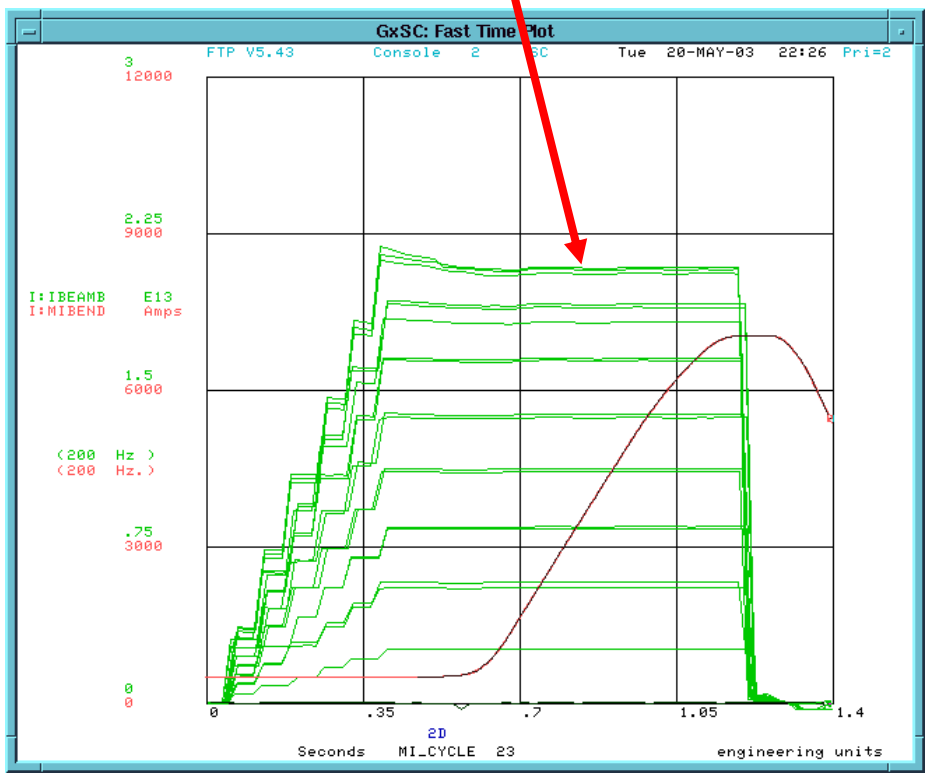


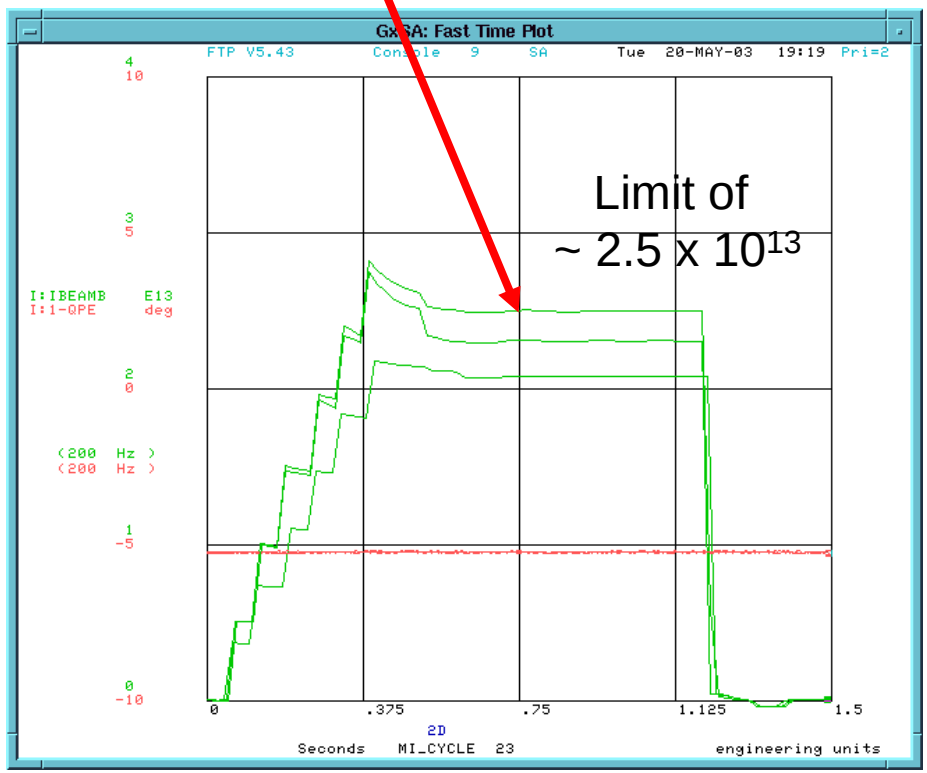
Starting multi-batch operation in MI

A. Marchionni, B. Choudhary, H. Kang, S. Mishra, R. Zwaska

May '03

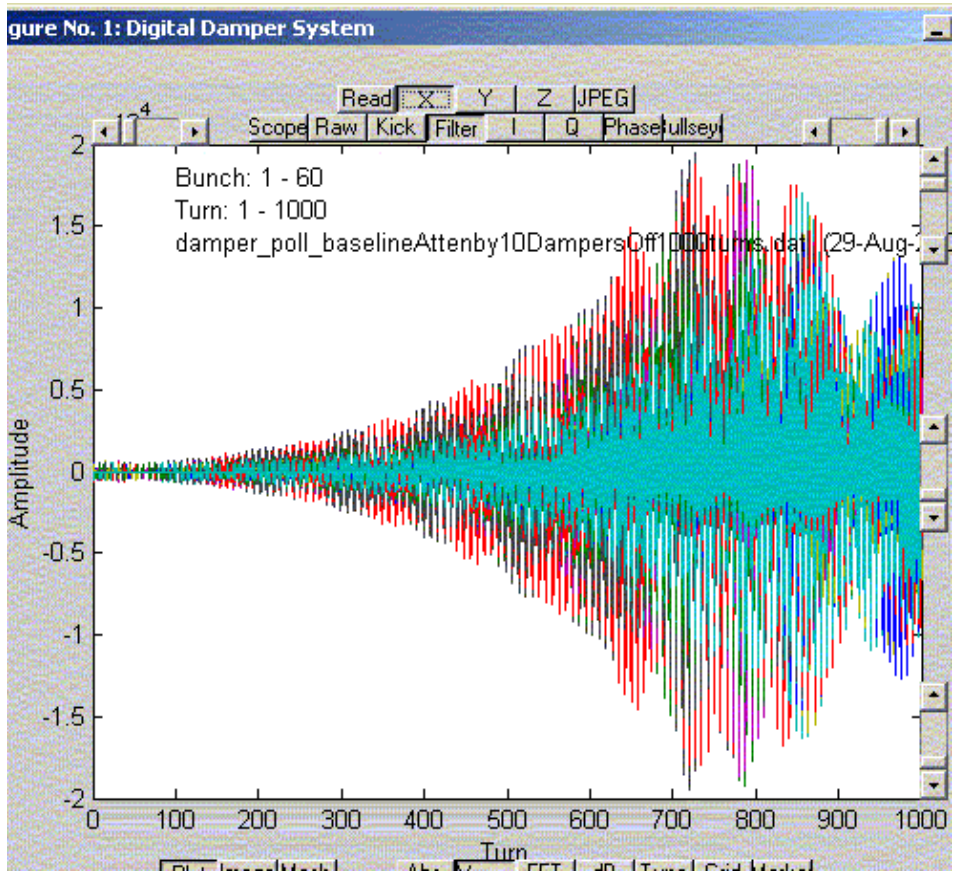
- 6 batches, increasing Booster turns
- 6 batches, 14 Booster turns





Damping Oscillations

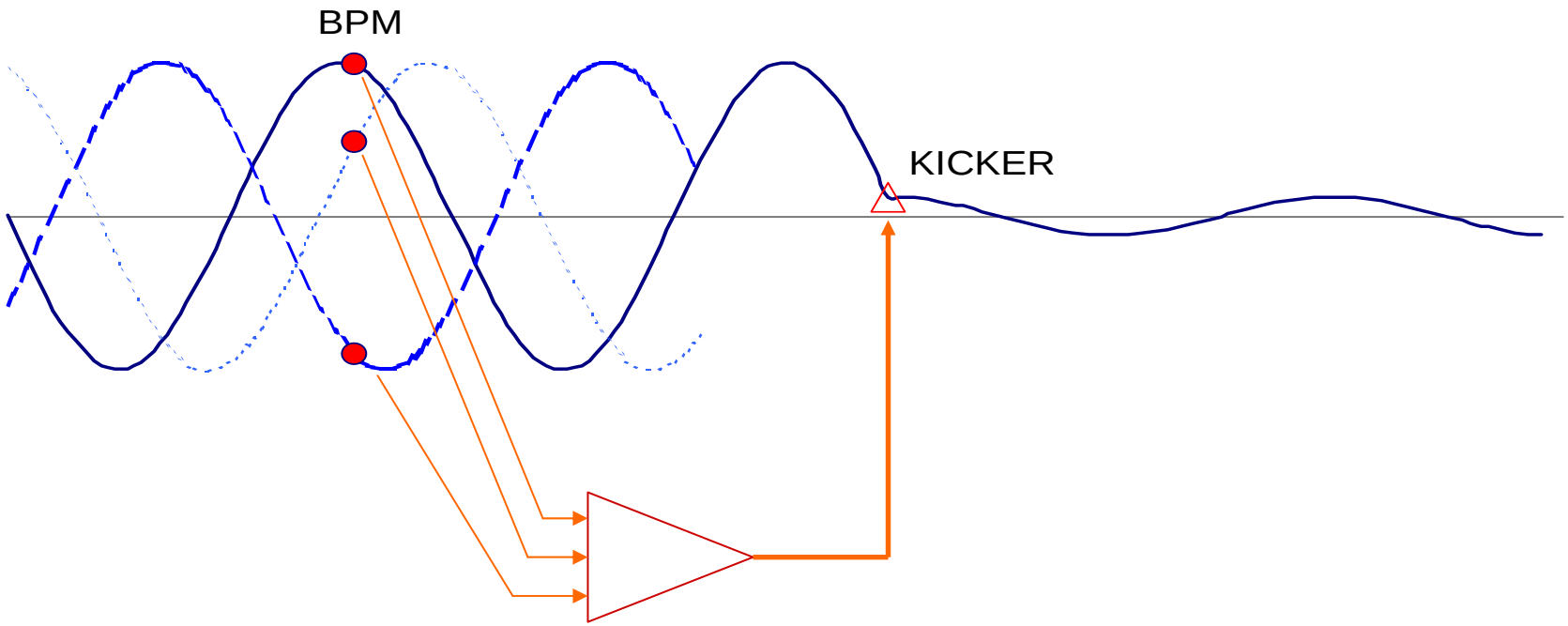
- Individual buckets of the beam oscillate about the ideal orbit
- Has many causes:
  - Injection errors
  - Intrabeam interactions
  - Magnetic field inhomogeneities
- Oscillations grow with time unless unchecked
- Previously, damper systems have only been able to damp specific modes of oscillation
- Digital technology allows a new method

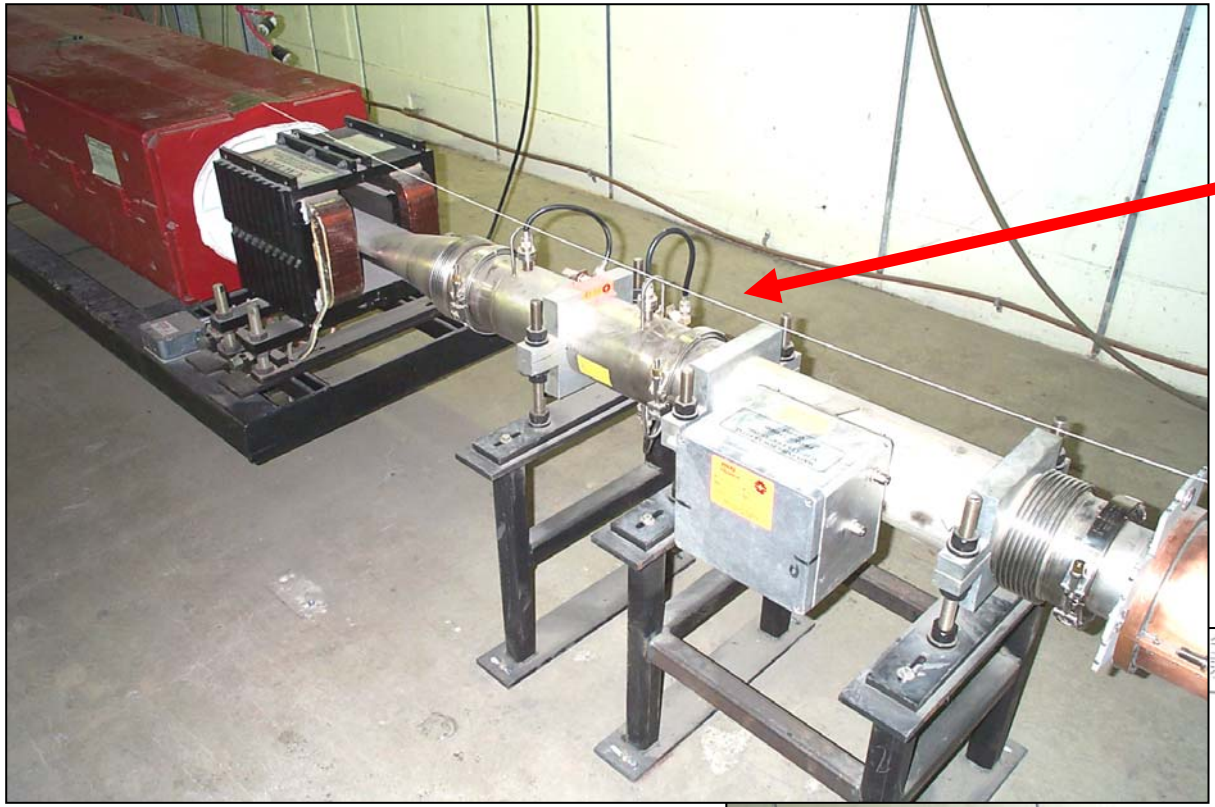


Digital Bunch-by-Bunch Dampers

B. Foster, H. Kang,

- Damp the oscillations of each bunch independently of the rest
  - More natural way to do it
- Requires very fast pickups, kickers, and electronics
  - Bunches are spaced 19 ns apart
  - Beam revolves in 11 μs
- Damper kick is calculated from single BPM position reading on 3 successive turns
  - Arbitrary Betatron Phase of Kicker can be accommodated
- Individual oscillations are damped in a few ms



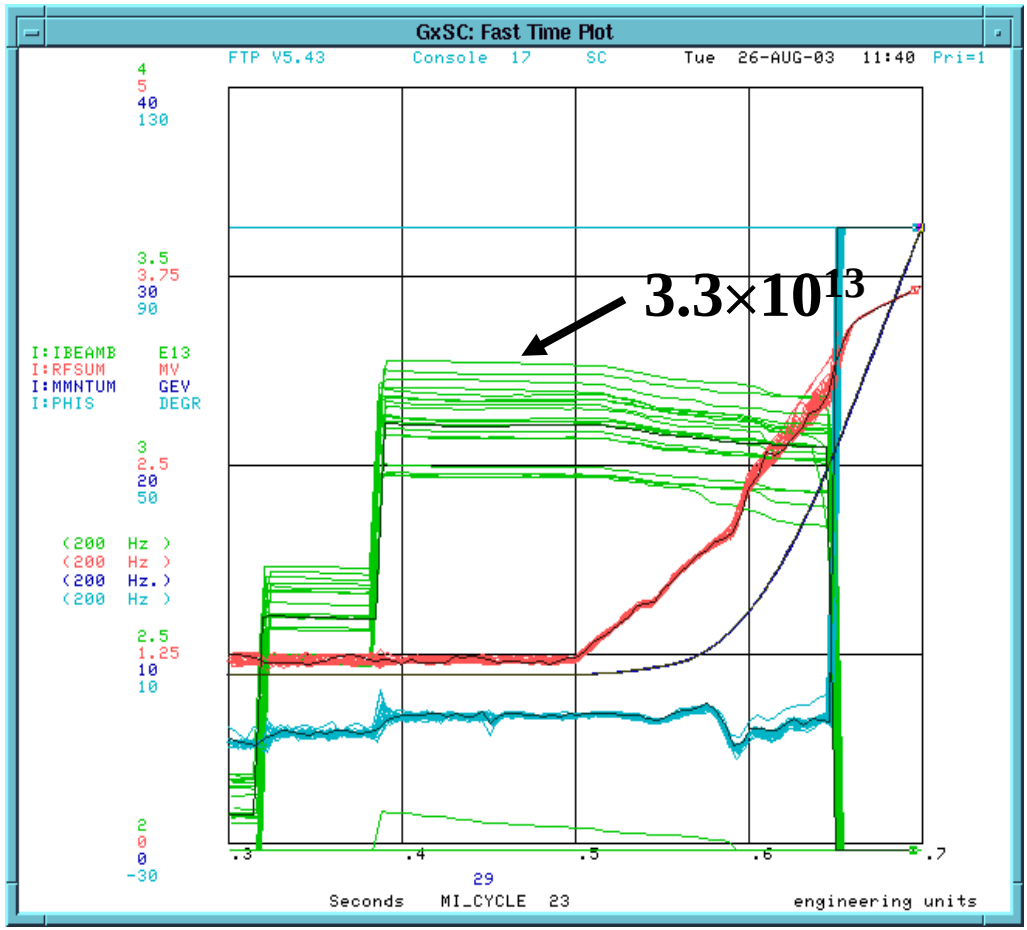


Horizontal
damper pickup

Longitudinal
kickers

Multibatch with Dampers

- Beam can survive injection
  - 3.3 x 10^{13} captured and accelerated to ~ 25 GeV
  - Enough for “baseline” operation
- Still cannot accelerate through transition because of RF
  - Primarily a matter of settings
  - Will be fixed soon



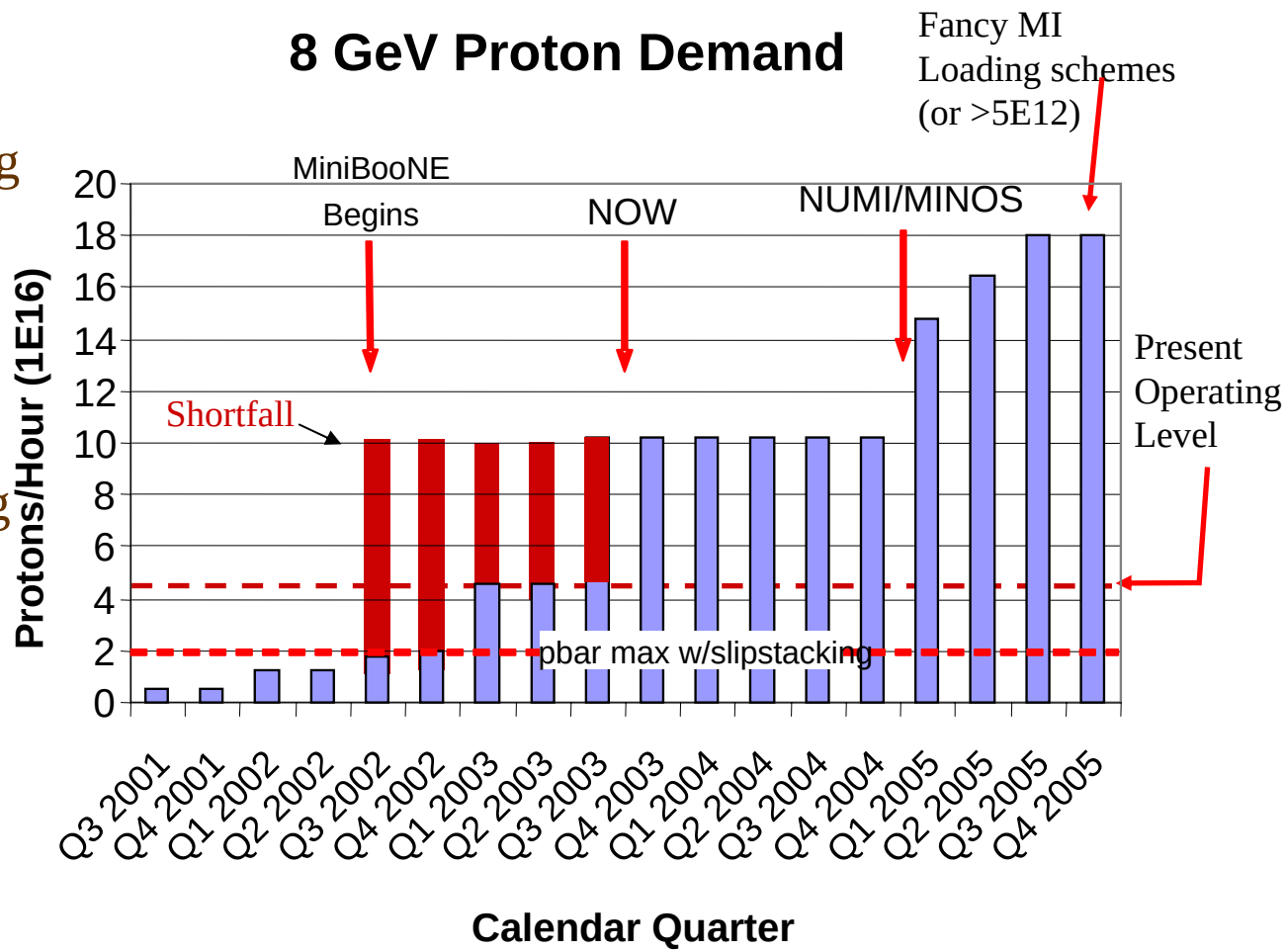
Main Injector Beam Permit for NuMI

S. Mishra, K. Wu

- This is required during operation and commissioning of the NuMI beamline,
  - Avoid beam losses in the NuMI beamline due to poor quality beam extracted from MI
- Needs a set of appropriate fast signals from Main Injector
  - Indicative of beam quality, need to be identified
- Signal provided to the NuMI permit system
  - Used to abort beam extraction to the NuMI beamline when the quality criteria are not met
- Beginning to write specifications for the system

“Proton Economics”

- Booster is the oldest ring at Fermilab
- Throughput has to increase several times
- Main Injector needs to finish its commissioning
  - Only accelerates one Booster batch now
  - Needs to do six

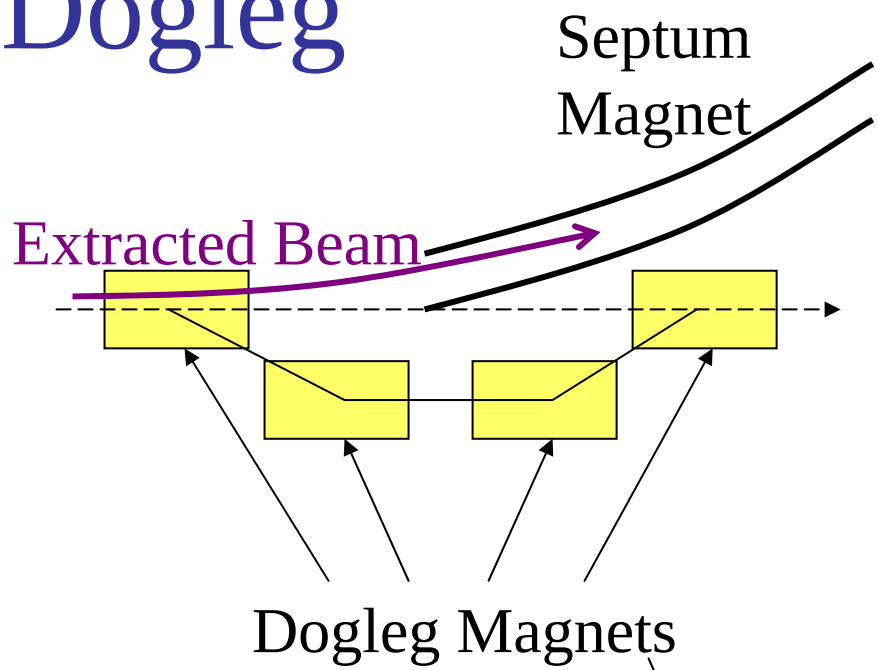


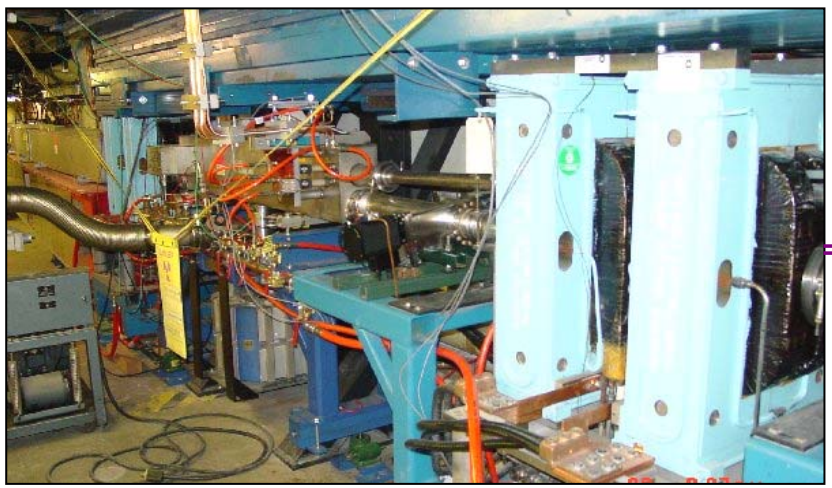
Booster as the Bottleneck

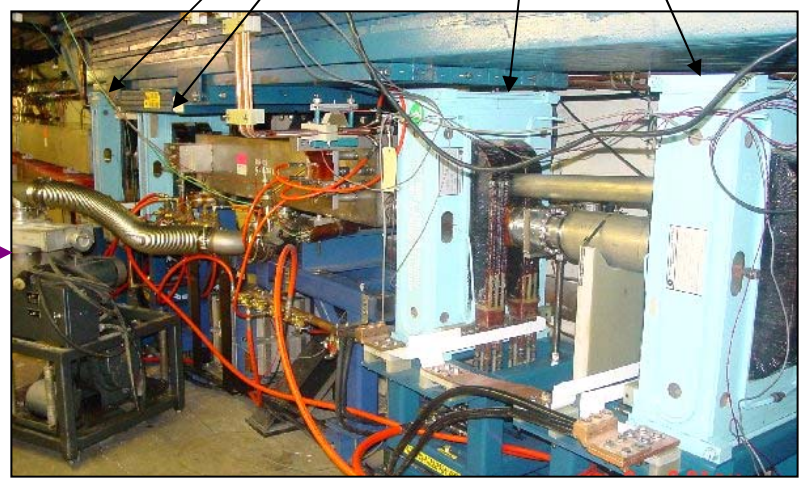
- Originally accelerated < 2 x 10^{12} once every few seconds
- Now needs to accelerate > 5 x 10^{12} at 5 – 8 Hz
- Pulsed devices became a major concern
  - Many have been upgraded/replaced
- Beam physics has to be understood on a new level
  - Space charge & instabilities
  - Details of magnet lattice
- Radiation becomes amore significant problems
  - Prompt radiation outside the tunnel increases
  - Radioactivation inside the tunnel also increases
  - Booster rate is limited by radiation from losses

Booster Dogleg

- Set of four DC dipole magnets know as a double "dogleg"
  - Also known as chicane
- Bends the beam around extraction septum magnet
- The dogleg magnets have edge focusing effects and higher order fields
  - Disturbs the lattice throughout the cycle, particularly during injection
  - Increases β by 50%
  - Increases Dispersion by 100%
- Fixed by increasing separation ⇔ reducing magnet strength







Radiation Issues

- Radiation is the driving limit on Booster operation
- Residual activation in the tunnel
  - Radioisotopes created by showers
  - Long lived isotopes limit how much maintenance can be done in the tunnel
- Damage of beam components
- Prompt radiation from the showering of lost protons
  - Radiation scales with energy and number of protons lost
  - Very small amount penetrates the shielding

Collimators

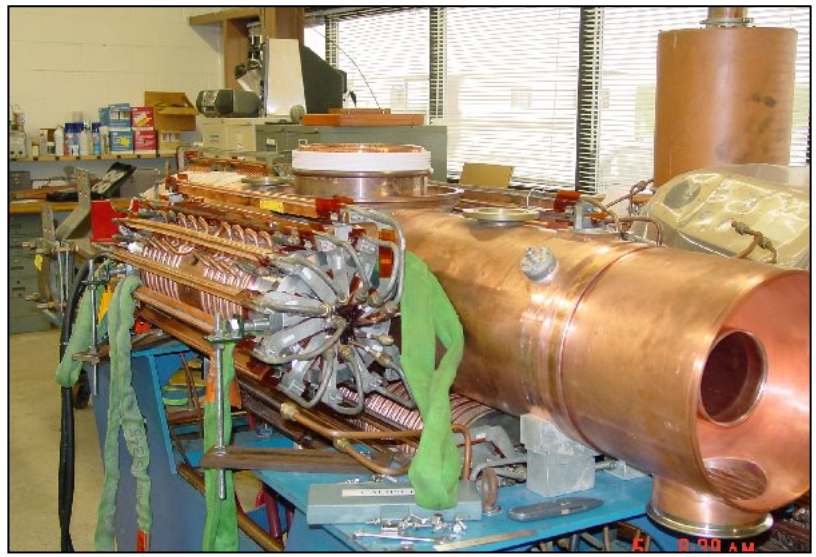
- Intentionally limit the aperture in a location
- Collect the resulting losses into three big blocks of steel

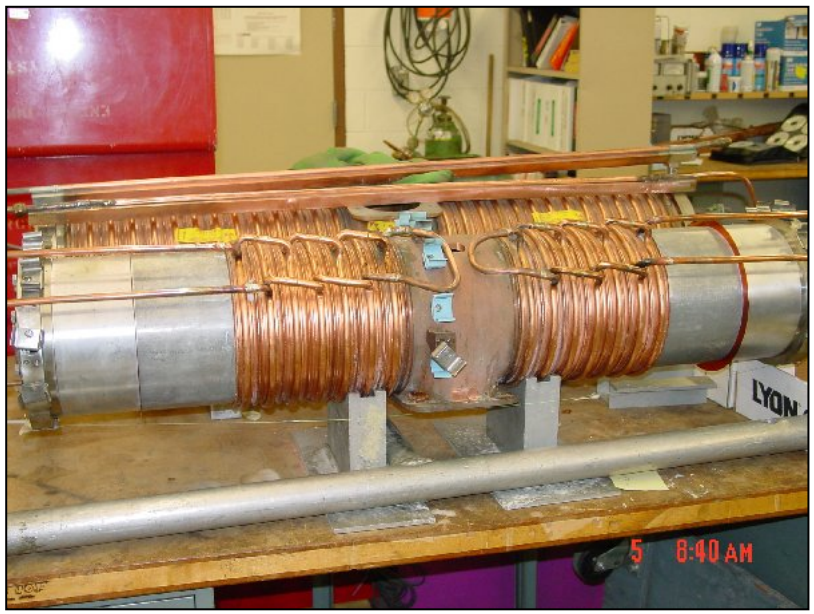
- Do not reduce losses in total
- Do reduce losses in critical areas
- Expected (hoped) to reduce uncontrolled losses by ~ 90%

RF Prototype Project

- Booster RF cavities
  - 18 in total around ring
  - Currently are the limiting aperture (2.3”)
  - Most losses occur in the RF cavities
  - Unfortunately most maintenance required is in the RF cavities!

- Plan: replace RF cavities with 5” aperture design from proton driver study

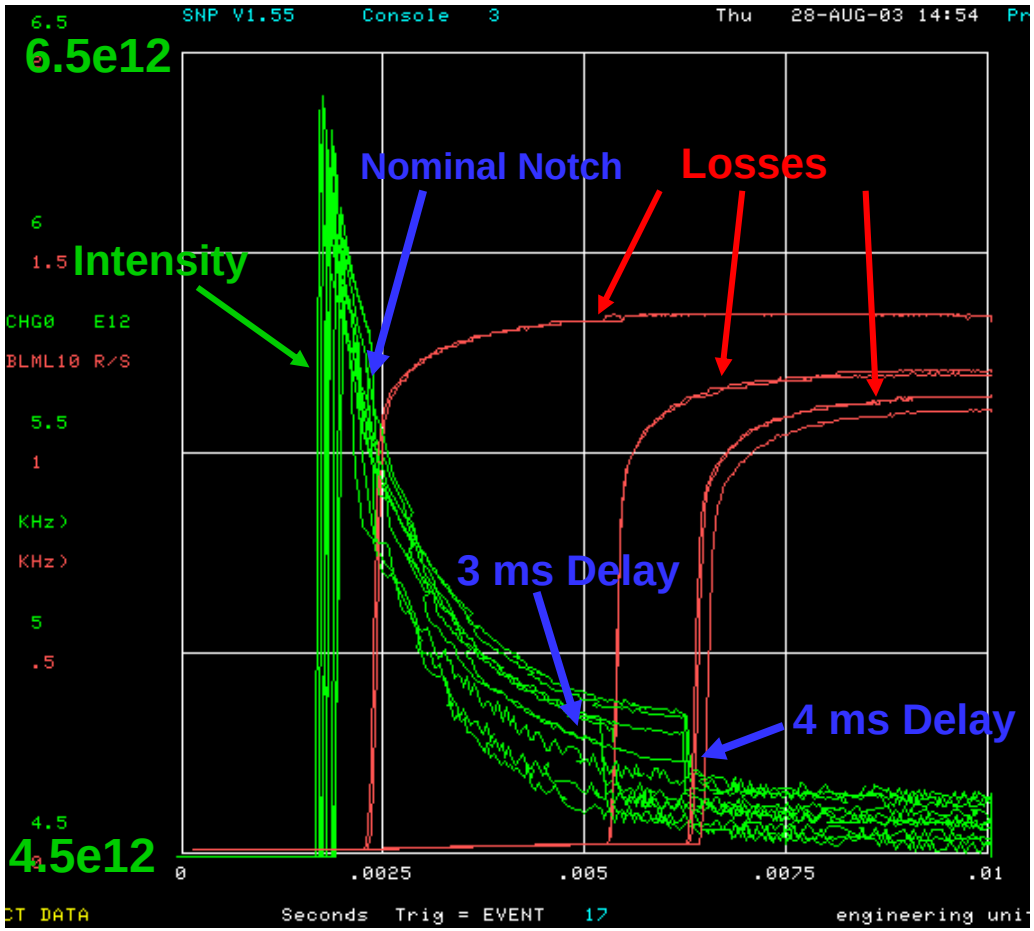




- Pilot program to replace two RF cavities. Universities involved:
  - MINOS: UT-Austin, Caltech, Tufts
  - MiniBoone: Indiana, Nevis, Princeton
- All parts machined, delivered in April/May, ready for assembly this summer
- Substantial savings to FNAL over in-house fabrication
- Intention to install this Fall ’03 shutdown, probably postponed til January.

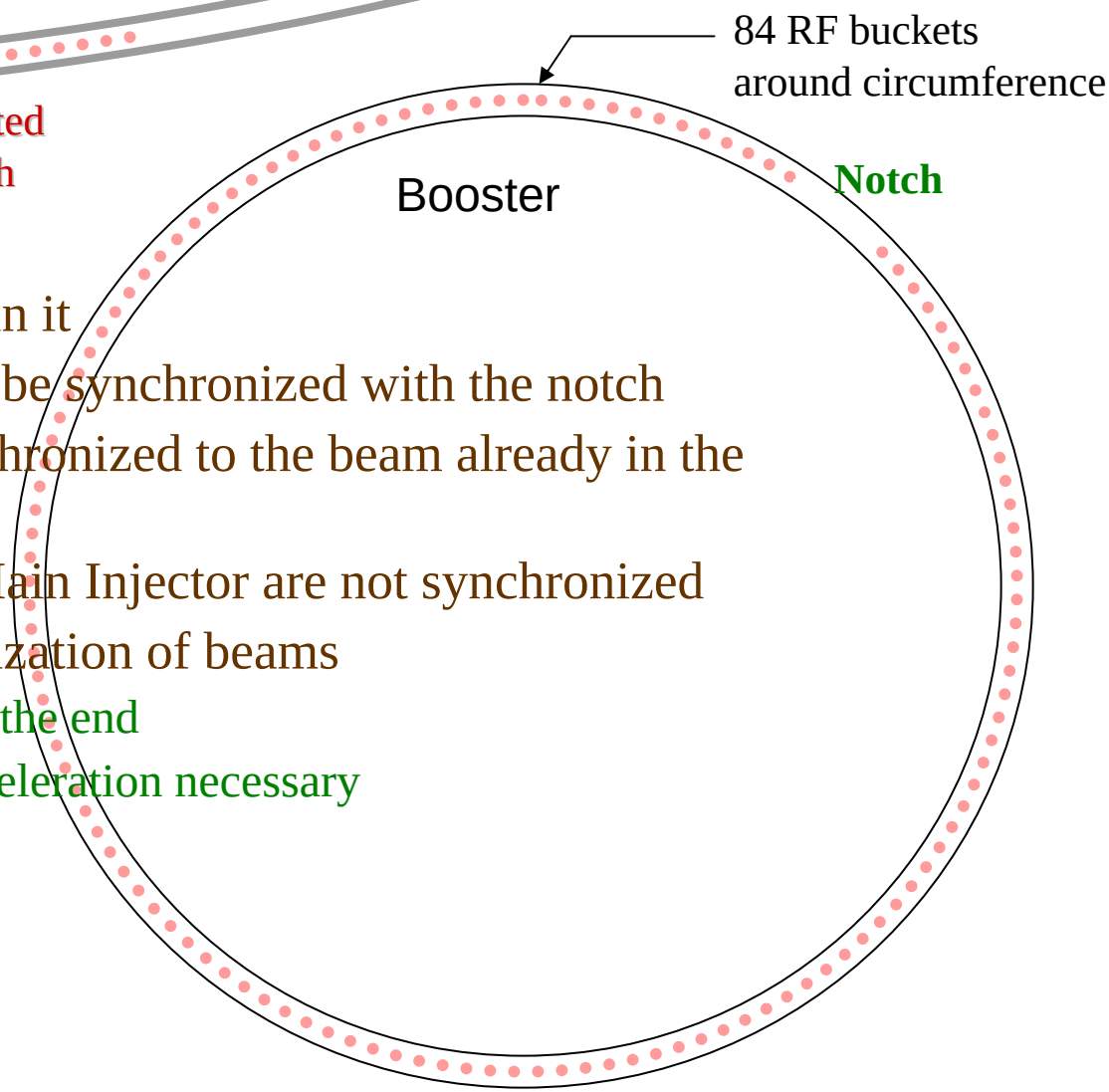
Need for a Notch

- Extraction kicker has a risetime of ~ 40 ns
  - Only ~ 10 ns between bunches
- Beam lost at 8 GeV
  - Losses on septum magnet
  - Already significant there
- 8 GeV losses would limit the PBar program
  - MiniBooNE & NuMI would be almost inoperable
- Instead, remove the beam at 400 MeV
  - Can choose where to lose it
  - Called a “notch” in the beam
- Beam currently notched with a fast kicker
  - Will be resonantly pinged into the collimators



Booster – MI Timing → Cogging

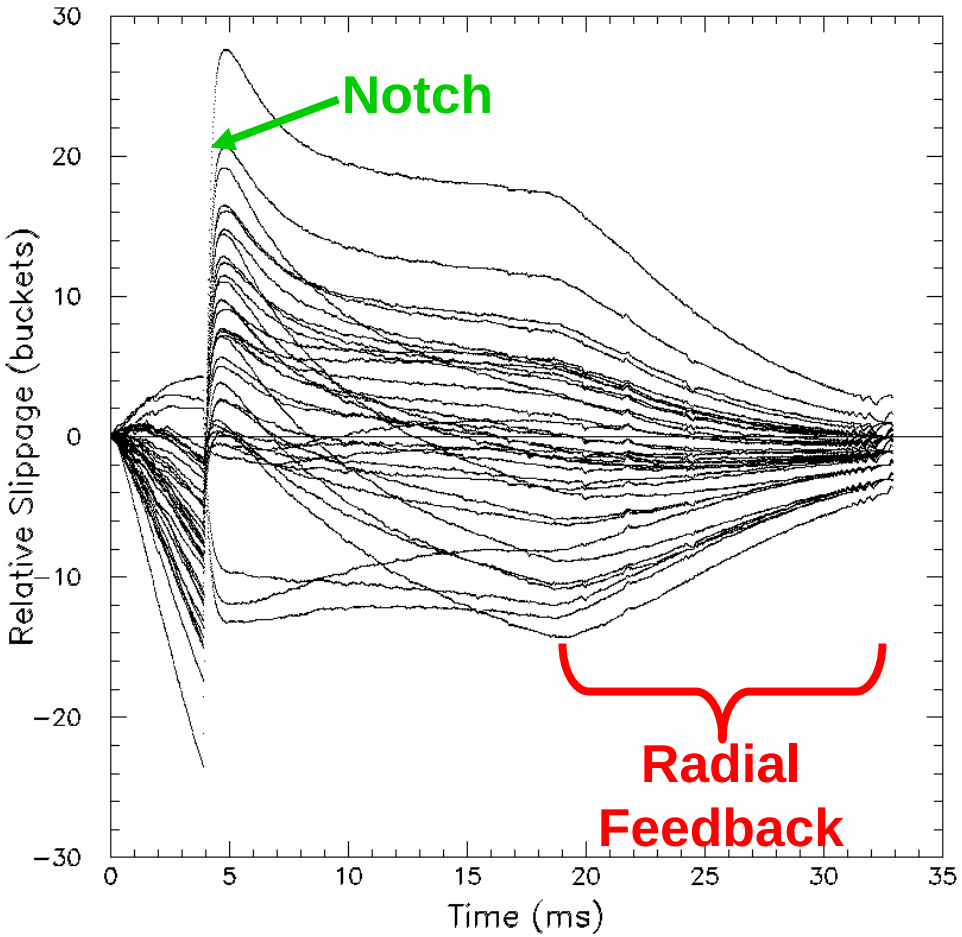
R. Zwaska, B. Pellico

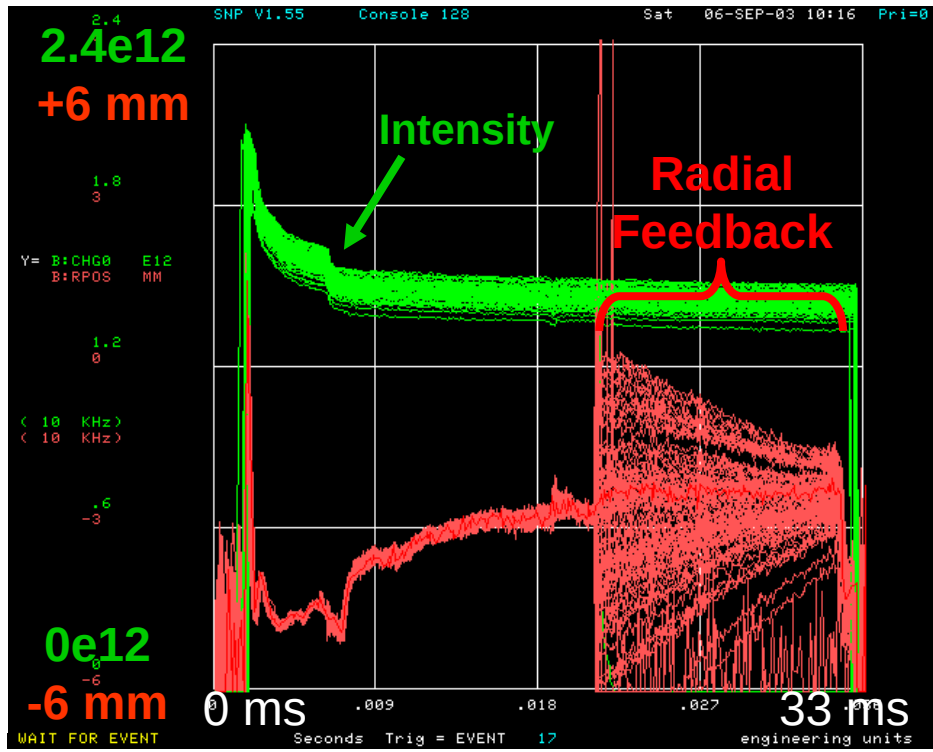


- Booster beam has the notch in it
- Requires extraction to MI to be synchronized with the notch
- Extraction must also be synchronized to the beam already in the Main Injector
- Problem: The Booster and Main Injector are not synchronized
- "Cogging": forced synchronization of beams
  - No Booster flattop to fix at the end
  - Active feedback during acceleration necessary

Cogging Beam Studies

- Predict relative slippage
  - Measure in first ~ 3 ms
  - Place notch intelligently
- Radial Feedback late in the cycle
  - Changes energy & circumference
  - Induces slippage





Summary

- NuMI is an entirely new mode of operation for Fermilab
  - Must run simultaneous with the Collider
- NuMI requires Main Injector to be commissioned for multibatch operation
  - MI designed for this, but never shaken out
  - Program underway to commission before NuMI turn-on
- Booster can potentially limit the program
  - Limited in per pulse intensity
    - Marginal improvements underway
  - Limited by radiation
    - Major improvements underway
    - Also important for MiniBooNE
  - Must be commissioned for multibatch operation → Cogging